

A Decomposed Negative Binomial Model of Structural Change: A Theoretical and Empirical Application to U.S. Agriculture

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We developed a single-equation decomposed negative binomial regression model (NBRM) of the U.S. farm sector to simultaneously evaluate structural changes in the U.S. agricultural sector and the strength of several economic forces that influenced the changes in farm structure during the 1960–96 period. We found all these forces reinforced economic incentives to increase the size and decrease the number of small farms. Only agricultural programs and machinery prices countered these forces.

Nous avons élaboré un modèle de régression binomiale négative (NBRM) décomposé à équation unique pour le secteur agricole des États-Unis afin d'évaluer simultanément les changements structurels de ce secteur ainsi que la puissance de plusieurs forces économiques qui ont influencé les changements de structure des exploitations agricoles au cours de la période 1960–96. Nous avons conclu que toutes ces forces ont renforcé les stimulants économiques en faveur d'une augmentation de la taille des exploitations et d'une diminution du nombre de petites exploitations. Seuls les programmes agricoles et le prix de la machinerie ont contrecarré ces forces.

INTRODUCTION

Rapid economic growth and technological advances in the United States during the last half century resulted in structural changes in the industrial and agricultural sectors. In an earlier study of the characteristics of production in U.S. agriculture, Lianos (1971) summarized findings from his study for the 1949–68 period as follows: first, U.S. agriculture is characterized by capital-intensive technological progress; second, the elasticity of substitution between labor and capital is greater than unity; and third, U.S. agricultural production technology is nonhomothetic. Following the introduction of Hayami and Ruttan's (1971) induced agricultural innovation theory, many economists have used various different models to demonstrate that U.S. agricultural production has biased technical changes, nonhomotheticities, and price-induced factor substitution. For example, Antle (1984) used a profit function for the 1910–78 period, Ray (1982) used a cost function for the 1939–77 period, and Thirtle, Schimmelpennig, and Townsend (TST) (2002) used a production function for the 1880–1990 period.

These studies, while useful, ignore a point made by Edwards in 1985 that aggregate farm productivity measures were not independent of the location of production spatially or by size of farm. As Edwards argued:

Changes in productivity are usually associated with technology. At the firm level, this is a natural way to think about productivity. However in aggregate analysis, measures of productivity can change even when technology does not. The measures change when the proportions of farms in stable technological situations change. . . . Changes in the proportions of farms that are large, incorporated, specialized, and operated by full-time farmers affect sector productivity. The productivity of the farm sector is partly a function of structure. (Edwards 1985, 1)

From an aggregate perspective, as all these studies were, the nature of production relationships are not independent of structure.¹

TST support Edward's insights by demonstrating that farm size also affects the observed rates and biases of technological changes. However, a physical unit rather than a pecuniary unit is used for the farm-size variable so that the estimated rates and biases of technical change may not adequately capture the size effects of the livestock sector, which represents half of U.S. farm market income.

The application of existing models for measuring structural changes in U.S. agriculture is handicapped by massive time-series data needs. Even though the model based on the translog profit function is theoretically superior to most other models, internally consistent estimation of large sectoral models can demand more than the available degrees of freedom. For instance, despite having 69 years of data, Antle notes:

The most efficient estimators of the translog profit function are obtained by jointly estimating equations (2) and (3), where equation (2) represents the translog profit function and equation (3) represents the normalized *i*th input cost share equation, which are derived from the all input demand and output supply equations that are obtained from the translog profit function by applying Hotelling's lemma. However, degrees of freedom are insufficient for direct estimation of the profit function (2). (Antle 1984, 417).

Meanwhile, TST used time-series data for the period between 1880 and 1990, but they acknowledged that the early data for the period between 1880 and 1910 involved interpolation, extrapolation, and estimation for some variables, which may be a source of inaccuracy in deriving inferences.

In this paper, we directly address the simultaneity of technology, productivity, and farm structure by developing a single-equation model of U.S. agriculture, a decomposed negative binomial regression model (NBRM), to test, in a consistent manner, hypotheses about size distribution, economies of size, nonhomotheticity of production technology, the marginal rate of technical substitution (MRTS), and the rates and biases of technical changes. This model is then applied to evaluate structural changes in the U.S. agricultural sector during the 1960–96 period.

The NBRM model we present is based on decomposed cost functions associated with different size classes. Estimating cost functions associated with different size classes maintains aspects of the near-perfect competitive nature of the farm sector. In particular, this approach assumes that all output and input prices are exogenous, i.e., no farms in a particular size class control sufficient input purchases or output sales to significantly influence prices.² While it may not be theoretically as strong as a profit function approach,

it requires much less time-series data for the parameter estimation than a translog profit function, a translog cost function, or a production function approach.

SIZE DISTRIBUTION, ECONOMIES OF SIZE, AND NON HOMOTHETICITY

If production technology of the farm sector can be characterized such that the same level of output could be produced in two size classes, a single operation y_{i+1} in the $(i + 1)$ th size class and $y_i = y_{i+1}/n_i$ in n_i separate operations in the i th size class, Chambers (1988, 70) demonstrated that in the multiple-size classes case there exists a number function $N_i(y_i)$, such that $n_i^\rho y_i = N_i(y_i)$ and

$$\begin{aligned} c_{i+1}(y_{i+1}(x_1, x_2, \dots, x_n)) &= n_i^{\rho(y_i(x_1, x_2, \dots, x_n))} c_i(y_i(x_1, x_2, \dots, x_n)) \\ &= N_i(y_i(x_1, x_2, \dots, x_n)) c_i(y_i(x_1, x_2, \dots, x_n)) \\ &\text{for } i = 1, 2, \dots, m - 1 \end{aligned} \quad (1)$$

where $c_{i+1}(y_{i+1})$ is the cost function associated with the output level y_{i+1} , $\rho(y_i(x_1, x_2, \dots, x_n))$ is the elasticity of total costs, x_k is the k th input, $c_i(y_i)$ is a cost function associated with the output level y_i , and m is the number of size classes. It should be noted from Eq. (1) that n_i is a constant, while $N_i(y_i)$ represents a number function.

When $\rho(y_i) = 1$, the farm is characterized as having a constant return to size, $n_i = N_i(y_i)$. When $\rho(y_i) > 1$, the farm exhibits diseconomies of size, $n_i < N_i(y_i)$. Similarly, when $\rho(y_i) < 1$ the farm exhibits economies of size, $n_i > N_i(y_i)$.

Differentiating both sides of Eq. (1) with respect to input price p_k associated with x_k results in the following:³

$$\partial c_{i+1}(y_{i+1})/\partial p_k = N_i(y_i) [\partial c_i(y_i)/\partial p_k] + c_i(y_i) [\partial N_i(y_i)/\partial p_k] \quad \text{for } i = 1, 2, \dots, m - 1 \quad (2)$$

Applying Shephard's lemma, Eq. (2) can be rewritten as follows:

$$x_k(y_{i+1}) = x_k(y_i) N_i(y_i) + c_i(y_i) [\partial N_i(y_i)/\partial p_k] \quad \text{for } i = 1, 2, \dots, m - 1 \quad (3)$$

Multiplying both sides of Eq. (3) by $(p_k/N_i(y_i))$ and using Eq. (1) gives

$$\begin{aligned} [\partial \ln N_i(y_i)/\partial \ln p_k] &= [p_k x_k(y_{i+1})/c_{i+1}(y_{i+1})] \\ &\quad - [p_k x_k(y_i)/c_i(y_i)] \quad \text{for } i = 1, 2, \dots, m - 1 \end{aligned} \quad (4)$$

The left-hand side from the equality in Eq. (4) represents the k th input price elasticity for the number of the i th size farms. The first and second terms of the right-hand side from the equality represent the k th input cost shares of the $(i + 1)$ th size farm and the i th size farm, respectively. Equation (4) indicates that the input price elasticity for the number of farms in each size class can be used to determine whether the changes in the structure of U.S. agriculture are associated with the k th factor-saving or the k th factor-using technical changes. If the right-hand side is positive (negative), the i th size farm is considered to have a k th input-saving (using) technical change.

Summing both sides of the equality in Eq. (4)

$$\begin{aligned}
\sum_{\kappa=1}^n [\partial \ln N_i(y_i) / \partial \ln p_k] &= \sum_{\kappa=1}^n [p_k x_k(y_{i+1}) / c_{i+1}(y_{i+1})] \\
&\quad - \sum_{\kappa=1}^n [p_k x_k(y_i) / c_i(y_i)] = \eta(y_i) \left| \sum_{\kappa=1}^n [\partial \ln(y_i) / \partial \ln p_k] \right| \\
&\quad - \eta(y_{i+1}) \left| \sum_{\kappa=1}^n [\partial \ln(y_{i+1}) / \partial \ln p_k] \right| \quad \text{for } i = 1, 2, \dots, m-1
\end{aligned} \tag{5}$$

where $\eta(y_i) = \rho(y_i(x_1, x_2, \dots, x_n))$ in Eq. (1) is the elasticity of total costs associated with the production of y_i from the i th size farm. The input price elasticities of output, indicated as $S_i = \sum_{\kappa=1}^n [\partial \ln(y_i) / \partial \ln p_k]$, represents a scale change, a change in output caused by a proportional change in all input prices. The production technology is nonhomothetic if $S_i \neq 0$ (see the Appendix and/or Antle 1984). Therefore, if the sum of all input price elasticities for the number of farms in each size class is nonzero, the production technology is nonhomothetic.

When the input price elasticities of output are the same across the size of farms, Eq. (5) can be rewritten as

$$\sum_{\kappa=1}^n [\partial \ln N_i(y_i) / \partial \ln p_k] = [\eta(y_i) - \eta(y_{i+1})] \left| \sum_{\kappa=1}^n [\partial \ln(y_i) / \partial \ln p_k] \right| \tag{6}$$

In the case of cost neutrality, Eq. (6) is further reduced as

$$\sum_{\kappa=1}^n [\partial \ln N_i(y_i) / \partial \ln p_k] = \eta(y_i) - \eta(y_{i+1}) \quad \text{for } i = 1, 2, \dots, m-1 \tag{7}$$

In Eq. (7) the larger size farm producing y_{i+1} reveals economies of size if $\eta(y_i) < \eta(y_{i+1}) < 1$ so that $\sum_{\kappa=1}^n [\partial \ln N_i(y_i) / \partial \ln p_k] < 0$ and the larger size farm operation is more cost effective than the smaller size farm operation. In this case economic forces can be expected to favor exits of farms from the smaller size farm class and entry or firm growth for farms in the larger size farm class. Similarly, if $1 > \eta(y_i) > \eta(y_{i+1})$, the smaller size farm operation is more cost effective than the larger size farm operation so that there would be economic forces to exit from the larger size farm class and for entry to the smaller size farm class.

To define the functional form of the $N_i(y_i)$ function, divide both sides of the equality in Eq. (4) by p_k , which results in

$$[\partial \ln N_i(y_i) / \partial p_k] = [x_k(y_{i+1}) / c_{i+1}(y_{i+1})] - [x_k(y_i) / c_i(y_i)] \quad \text{for } i = 1, 2, \dots, m-1 \tag{8}$$

Integrating both sides of Eq. (8) results in the following exponential form:⁴

$$\begin{aligned}
N_i(y_i) &= \exp \left(\int [x_k(y_{i+1}) / c_{i+1}(y_{i+1})] - [x_k(y_i) / c_i(y_i)] \delta p_k \right) \\
&= \exp \{ [p_k x_k(y_{i+1}) / c_{i+1}(y_{i+1})] - [p_k x_k(y_i) / c_i(y_i)] \} \\
&= \exp[\eta_i(p_k)] \quad \text{for } i = 1, 2, \dots, m-1 \quad \text{and } k = 1, 2, \dots, n
\end{aligned} \tag{9}$$

where $\eta_i(p_k) = [\partial \ln N_i(y_i) / \partial \ln p_k]$ from Eq. (4). The result in Eq. (9) indicates that the number function, $N_i(y_i)$, is represented by an exponential function of all input price elasticities for the number of farms in each size class.

Since the number of farms for each size class is a *count variable*, use of the ordinary regression model would result in inefficient, inconsistent, and biased estimators. Therefore, in the following section we present a single-equation decomposed NBRM for U.S. agriculture,⁵ which acknowledges the diverse effects of economic factors by size class, yet whose degrees of freedom requirements are not a limiting concern.

A DECOMPOSED NEGATIVE BINOMIAL REGRESSION MODEL FOR THE U.S. AGRICULTURAL SECTOR

Adopting a classification system for farms by size provides a foundation to better understand the causes of the changing number and size of farms. We use the farm typology groups constructed by the Economic Research Service of the U.S. Department of Agriculture (ERS/USDA) that classify all farms with annual gross sales less than \$250,000 as smaller size farms. For the purposes of this study these smaller size farms are further grouped into two size groups that we call small-size and medium-size farms. Small-size farms represent farms with annual sales less than \$100,000 (a combination of ERS limited-resource, retirement, residential/lifestyle, and farming occupation/lower sales farms). Medium-size farms represent farms with annual sales between \$100,000 and \$250,000 whose operator identified farming as his or her primary occupation. All farms with annual sales greater than \$250,000 are classified as large-size farms. Under these size classifications, the reduction in the number of U.S. farms in the past came from the declining number of small-size farms, which steadily declined from more than 3.8 million in 1960 to 1.7 million in 1996. The number of medium-size farms and large-size farms steadily increased, with minor fluctuations, during the same period from 95,000 to 212,000 and from 24,000 to 141,000, respectively.

To be consistent with the number function presented in Eq. (9), we adopt the following specification of the decomposed NBRM of structural changes in the U.S. farm sector, consistent with cost minimization while recognizing and considering the effect of the volatility of farm output prices on factor commitment and the efficacy of agricultural research expenditures and government payments:

$$\begin{aligned}
 & E[N_{j,t} | (w/P_y)_t, (r/P_y)_t, (k/P_y)_t, (G/P_y)_t, (R/P_y)_t] \\
 &= \exp \left\{ \alpha_0 + \sum_{i=1}^3 \alpha_i D_i(w/P_y)_t + \sum_{i=1}^3 \beta_i D_i(r/P_y)_t \right. \\
 & \quad \left. + \sum_{i=1}^3 \gamma_i D_i(k/P_y)_t + \sum_{i=1}^3 \delta_i D_i(G/P_y)_t + \theta(R/P_y)_t + \sum_{i=1}^2 \lambda_i D_{i,t} + \varepsilon_{j,t} \right\} \quad (j = 1, 2, 3)
 \end{aligned} \tag{10}$$

where the subscripts $i = j = 1$ are for small-size farms, $i = j = 2$ are for medium-size farms, and $i = j = 3$ are for large-size farms; and where

N_j = the number of farms which are in farm-size category j

w = the index of hourly wage of farm workers (1992 = 100),

r = the index of average interest rates of 3 year and 10 year yields (1992 = 100),

k = the index of machinery prices paid by farmers (1992 = 100),

P_y = the index of output prices received by farmers (1992 = 100),

R = annual agricultural research expenditures (in 1992 dollars),

G = government payments for farm programs,

D_i = a dummy variable associated with the i th farm-size class such that

$D_i = 1$ if $i = j$, and $D_i = 0$ otherwise,

The wage rate, interest rate, and machinery price elasticities for the number of farms in each size class estimated from Eq. (10) must be consistent with the number function presented in Eq. (9). Results obtained from Eq. (10) are represented in Eqs. (11)–(13), respectively, as:

$$\eta_i(w) = [\partial E(N_i)/\partial w][w/E(N_i)] = \alpha_i(w/P_y) \quad i = 1, 2, 3 \quad (11)$$

$$\eta_i(r) = [\partial E(N_i)/\partial r][r/E(N_i)] = \beta_i(r/P_y) \quad i = 1, 2, 3 \quad (12)$$

$$\eta_i(k) = [\partial E(N_i)/\partial k][k/E(N_i)] = \gamma_i(k/P_y) \quad i = 1, 2, 3 \quad (13)$$

In general, smaller farming operations are more labor intensive and larger farming operations are more capital intensive. As the wage rate rises, farms of all size achieve economic efficiency by replacing labor with machinery.⁶ Therefore, from Eq. (10), the sign of α_i is expected to be negative for small-size farms and positive for large-size farms. In general, the sign of the parameters β_i and γ_i associated with the rate of interest and the price index of machinery, respectively, are likely to be opposite the sign on wages. But with large-size farms the varying financial capital and machinery capital intensities of farms in the size class complicate the identification of predominant economic forces that determine the expected sign.

The sign of the parameter δ_i , associated with normalized government expenditures for farm programs, represents how government programs affect farm numbers. For small-size farms, when the estimate is negative, government farm programs are expected to have a negative effect on changes in farm numbers as Cochrane (1993) and as Quance and Tweeten (1972) have noted. If the parameter estimate is positive, this would indicate that government farm programs would help small-size farms to stay in farm production as Stanton (1978), Gardner (1978), and Richardson et al (1988) have claimed. However, if the parameter estimate is statistically insignificant or is statistically significant but it is small enough so that $[\partial E(N_i)/\partial G]$ in Eq. (10) is negligible, then government farm programs would be expected to have no impact on farm size and number as Spitze et al (1980) noted.

The rapid innovations in mechanical technologies that occurred during the earlier part of the last century, which resulted in rapid structural change, were capital-embodied indivisible technologies, and hence exhibited a farm-size bias. The innovations in chemical and biological technologies were less size biased, yet these innovations still created incentives for farm structural changes (Batte and Johnson 1993).

BIASED TECHNICAL CHANGE IN THE U.S. FARM SECTOR

While the sum of all input price elasticities for the number of farms in each size class reveals whether there are economies of size as shown in Eqs. (5)–(7), and whether the technical change is labor intensive or capital intensive as shown in Eq. (4), we show it does not reveal the magnitude of bias of technical changes.

To evaluate how labor and financial capital have been employed in the U.S. farm sector, we use a modified Hick's approach to measuring the bias of technical change as follows:

$$B_{i,i+1} = \{[\Delta(MP_C/MP_L)_i/\Delta i]/(MP_C/MP_L)_i\} \quad \text{for } i = 1, 2 \quad (14)$$

The subscripts, C and L , represent financial capital and labor, respectively, and the subscript i represents the size of farm. Bias of technical progress, $B_{i,i+1} > 0$, indicates that as the farm size increases from the i th size class to the $(i+1)$ th size class, technical progress increases the marginal product of financial capital relative to that of labor. Similarly, $B_{i,i+1} < 0$ indicates that as the size of farm increases from the i th size class to the $(i+1)$ th size class, technical progress increases the marginal product of labor relative to the marginal product of financial capital.

To estimate the MRTS of labor for financial capital, MRTS of L for C , the output price elasticity for the number of farms in each size class is represented by

$$\begin{aligned} \eta_i(P_y) &= [\partial E(N_i)/\partial P_y][P_y/E(N_i)] \\ &= -[\alpha_i(w/P_y) + \beta_i(r/P_y) + \gamma_i(k/P_y) + \delta_i(G/P_y) \\ &\quad + \theta(R/P_y)] \quad \text{for } i = 1, 2, 3 \end{aligned} \quad (15)$$

The result in Eq. (15) indicates that the output price elasticity for the number of farms equals the negative sum of the elasticities of labor, financial capital, machinery capital, government expenditures for farm programs, and publicly financed agricultural research expenditures for the number of farms in each size class. Equation (15) can then be rewritten as follows:

$$\eta_i(P_y)_\theta = -[\alpha_i(w/P_y) + \beta_i(r/P_y)] \quad \text{for } i = 1, 2, 3 \quad (16)$$

where $\eta_i(P_y)_\theta = \eta_i(P_y) + \gamma_i(k/P_y) + \delta_i(G/P_y) + \theta(R/P_y)$.

Because at optimal production levels each input is used up to a point where the value of marginal product equals the unit price of that input, Eq. (16) can now be rewritten as

$$\eta_i(P_y)_\theta = -[\alpha_i MP_L(i) + \beta_i MP_C(i)] \quad \text{for } i = 1, 2, 3 \quad (17)$$

where MP_L and MP_C represent the marginal product of labor and the marginal product of financial capital, respectively. The MRTS of labor for financial capital for the i th size farms, $(MP_C/MP_L)_i$, derived from Eq. (17), is given by

$$[MP_C/MP_L]_i = -[\alpha_i/\beta_i] - [\eta_i(P_y)_\theta/(\beta_i MP_L(i))] \quad \text{for } i = 1, 2, 3 \quad (18)$$

To estimate the MRTS of labor for financial capital, assume in Eq. (18) that $MP_C(i) = 1$ for all i . The marginal product of labor for the i th size farms, when $MP_C(i) = 1$ for all i , is then represented as follows:

$$MP_L(i) | (MP_C(i) = 1) = -[\eta_i(P_y)_\theta + \beta_i] / \alpha_i \quad \text{for } i = 1, 2, 3 \quad (19)$$

and the MRTS of labor for financial capital in Eq. (18) is then estimated by

$$[MP_C/MP_L]_i = -\alpha_i / [\eta_i(P_y)_\theta + \beta_i] \quad \text{for } i = 1, 2, 3 \quad (20)$$

Equation (20) is used to estimate bias in technical change presented in Eq. (14).

EMPIRICAL RESULTS

Farm size as defined by the value of products sold is a useful measure for a given year. However, the effects of price changes blur the boundaries between size classifications over time so that a time-series analysis of structural change requires consistent boundaries in the definition of farm size. Therefore, data on the number of farms in each size class are obtained from Teigen (1996), who estimated the annual number of farms with constant volume of output in 1992 dollars by using a Trapezoidal density function.⁷

Data on publicly financed agricultural research expenditures followed the approach of Huffman and Evenson (1993), using the sum of the annual expenditures (in million of 1992 dollars) for the Experiment Station Research and Cooperative Agricultural Extension. Government program payments include deficiency payments, disaster payments, and conservation reserve payments. Time-series data on total government payments from various volumes of USDA's *Agricultural Statistics* are reported as a component of U.S. gross farm income (USDA 1960–96). We used the index of prices received by farmers (also from *Agricultural Statistics*) for the farm output price. Prices received represent sales from producers to first buyers and are averaged over all grades, qualities, and commodities including all crops, dairy products, and livestock and livestock products. The hourly nominal farm wage rates (without room and board) were also acquired from *Agricultural Statistics*. The rate of interest, r , an average of 3-year and 10-year bond yields, was obtained from various issues of the *Economic Report of the President* (U.S. Council of Economic Advisors 1960–1996). Both wage rates and interest rates were indexed to base year 1992.

The annual data on the number of farms in each of three size classes covering the period between 1960 and 1996, provide 111 observations for parameter estimation, enough observations to apply a maximum-likelihood method. The EViews software was used to estimate the decomposed NBRM, Eq. (10), with a maximum-likelihood method. Parameter estimates are presented in Table 1. The sign of parameter estimator α_1 associated with the normalized wage variables, (w/P_y) , for small-size farms is negative, while the signs of parameter estimators, $\alpha_i (i = 2, 3)$ for medium-size and large-size farms are positive. These results confirm our expectation that as the wage rate increases small-size farm operators find their labor costs increasing proportionately more. If small-size farm operators attempt to achieve economic efficiency by switching from a labor-intensive operation to a capital-intensive operation some may fail and leave the sector. Others may succeed, but in the process grow to medium-size farm operations. Either way, the number of small-size farms would decline and the number of medium and large-size farms would increase as small operators mechanize and become larger.

Parameter estimator γ_1 associated with normalized machinery prices, k/P_y , for small-size farms is positive, while parameter estimators $\gamma_i (i = 2, 3)$ for medium-size

Table 1. Parameter estimates for a decomposed negative binomial regression model of U.S. farm structural changes

Parameter	NBRM Estimates	
	Coefficient	Standard error
Constant	2.3873**	0.2644
<i>Normalized wage of labor (w/P_y)</i>		
α_1	-1.8882**	0.3209
α_2	1.6400**	0.3849
α_3	2.7665**	0.4995
<i>Normalized rent for financial capital (r/P_y)</i>		
β_1	-0.0617	0.0613
β_2	0.2002**	0.0771
β_3	0.2729**	0.0966
<i>Normalized machinery price (k/P_y)</i>		
γ_1	0.7106*	0.2894
γ_2	-0.4403	0.3307
γ_3	-0.1125	0.4190
<i>Normalized farm program expenditures (G/P_y)</i>		
δ_1	0.0028**	0.0007
δ_2	-0.0005	0.0008
δ_3	-0.0025*	0.0010
<i>Normalized research expenditure (R/P_y)</i>		
θ	-0.0232**	0.0070
<i>Dummy variable</i>		
λ_1	6.5128**	0.2938
λ_2	1.9694**	0.3159

Subscripts 1, 2, and 3 represent small-size farms, medium-size farms, and large-size farms, respectively.

* and ** represent that the estimate is statistically significant at the 95% confidence level and at the 99% confidence level, respectively.

and large-size farms, respectively, are negative, but not statistically significant. Being the opposite of the wage case, operators of the more labor-intensive small-size farm operations find their machinery costs rising proportionately less than operators of the more capital-intensive large farm operations. If medium and large-size farm operators attempt to achieve economic efficiency by switching from a capital-intensive operation to a more labor-intensive operation some may fail and leave the sector. Others may succeed, but in the process downsize to a smaller size farm operation. Either way, the number of medium and large-size farms would decline and the number of small-size farms may increase or at least decline at a slower rate.

The parameter estimator associated with the normalized rates of interest for small-size farms is negative, although statistically insignificant, while those for medium-size and large-size farms are positive. The rate of interest normalized with the output price index declined by 49% from 1960 to 1996, encouraging farm operators to make more capital

Table 2. Estimated elasticities of input and output prices for the number of farms in each size class, measured at mean values

Farm-size class	$\eta_i(w)$	$\eta_i(r)$	$\eta_i(k)$	$\eta_i(g)$	$\eta_i(R)$	$\eta_i(p_y)$
<i>Small-size</i>	-1.3784 (0.2343)	-0.0870 (0.0864)	0.5258 (0.2142)	0.1896 (0.0473)	-0.3025 (0.0913)	1.0525 (0.6735)
<i>Medium-size</i>	1.1972 (0.2810)	0.2823 (0.1087)	-0.9852 (0.2447)	0 ^a	-0.3025 (0.0913)	-0.1918 (0.7257)
<i>Large-size</i>	2.0195 (0.3646)	0.3847 (0.1362)	0 ^a	-0.1667 (0.0676)	-0.3025 (0.0913)	-1.9350 (0.6597)

Numbers in parentheses represent the standard error.

^aParameter estimate was statistically insignificant at the 69% confidence level so that the input price elasticity for the number of farms was considered to be zero. The 69% confidence level was chosen to preserve a larger number of significant elasticities.

investments. The normalized, hired farm labor wage rate and machinery prices increased by 126% and 84%, respectively, during the same period. Because land is usually the chief asset for a farm operation and the rate of interest (normalized with the output price) fell relative to farm wages and machinery prices, users of financial capital (e.g., farmland buyers who buy land from neighboring farms) were favored economically. Results for the parameter estimator associated with the normalized rate of interest reflect this input price difference and the greater sensitivity of farms in the two larger size classes to the cost of financial capital.

The parameter estimate associated with normalized government expenditures for farm programs is positive for small-size farms and negative for large-size farms, but it is statistically insignificant for medium-size farms. A possible explanation for this result is the distribution of farms and ranches that make up our three farm-size groups. Over 80% of all U.S. farming operations fall into the small-size farm category. Over half of these farms report negative farm income and rely mostly on off-farm earnings for household income. While the total government expenditure to any particular farm may be insignificant, government payments may contribute a substantial share of these farms' total farm income. On the other hand, many large-size farms are classified as large because they produce high-value agricultural products that are not eligible for government payments. Government program payments are primarily paid for field crops and many of the farms in the larger size groups do not grow program crops.

The parameter estimate associated with publicly financed agricultural research expenditures is negative. This result may indicate that the number of both medium-size and large-size farms increase as a result of publicly financed agricultural research, while the number of the more abundant small-size farms declines. An increase in yield resulting from agricultural research would translate into reducing average production costs. As we shall see later, technological progress in farming has increased the marginal product of financial capital relative to that of labor, benefiting the more capital-intensive medium-size and large-size farms compared to small-size farms.

The estimated elasticities of input prices for the number of farms in each size class are presented in Table 2. Consistent with expectations that small-size farms use more

Table 3. Estimated marginal rate of technical substitution of labor for financial capital in each size class and biased technical change of the U.S. farm sector

Farm-size class	MP_C/MP_L	$B_{i,i+1}$
<i>Small-size</i>	0.1345	8.5316
<i>Medium-size</i>	1.2820	0.0125
<i>Large-size</i>	1.2980	

labor-intensive technology, while medium-size and large-size farms use labor-saving technologies, the elasticity of the normalized wage variable for the number of small-size farms is negative, while those for medium-size and large-size farms are positive.

Small-size farms are expected in general to be characterized as capital-saving operations, while large-size farms are capital-intensive operations. However, the estimated elasticity of the normalized interest rate is negative for small-size farms, but it is positive for medium-size and large-size farms. As previously suggested, the relatively low rates of interest during the 1960–96 period may have encouraged aggressive farmers to increase the size of their farms by buying land (making more land investments). The estimated elasticity of machinery capital for the number of farms is positive for small-size farms and negative for medium-size farms. The parameter estimate for large-size farms was not statistically significant. These results imply, as expected from Eq. (4), that small-size farms have machinery capital-saving technology, while medium-size farms have machinery capital-using technology.

The output price elasticity for the number of farms in each size class equals the negative sum of the input price elasticities for the number of farms in each size class as shown in Eq. (15). Therefore, the aggregate input price elasticity for the number of farms in each size class (Table 2) is negative for small-size farms, while it is positive for medium-size and large-size farms, respectively. These results are consistent with U.S. agriculture (in aggregate) being characterized with a nonhomothetic production technology, and with economies of size in small-size farms.

The marginal rates of technical substitution (MRTS) of labor for financial capital, estimated with Eq. (20), for each farm-size class are presented in Table 3. Results show that the marginal products of financial capital are less than the marginal products of labor for small-size farms, but the marginal products of financial capital are greater than the marginal products of labor for medium-size and large-size farms. The MRTS of labor for financial capital increases as farm-size class increases. The MRTS of labor for financial capital is 0.13 for small-size farms, 1.28 for medium-size farms, and 1.30 for large-size farms.

The parameter for the bias of technical change between small-size farms and medium-size farms is estimated to be $B_{1,2} = 8.532 > 0$. This result may imply that technological progress increased the marginal product of financial capital relative to that of labor with shifts from small-size to medium-size farms. This would give an incentive for small-size farm operators to substitute financial capital for labor to increase the capital–labor ratio. These results are somewhat consistent with earlier findings that the elasticity of

substitution is greater than unity and that U.S. agriculture is characterized by capital-using technological progress (Kaneda 1967; Lianos 1971; Binswanger 1974; Ray 1982; Antle 1984; TST 2002).

The bias of technical change between medium-size and large-size farms is estimated to be $B_{2,3} = 0.012 > 0$. This result is consistent with our earlier finding that there are no economies of size for medium-size or large-size farms. The implications of these results are significant for policy makers. With a relatively fixed farmland base, as the number of farms has steadily declined, the size of farms has steadily increased. The primary focus of small-size farms is often not necessarily to operate the farm at a profit, but rather, the farm objective is often viewed by the operator as a "way of life," that is, owning property with farm resources being used for agriculture, but with the main source of household income coming from off-farm sources. The increases in the marginal product of financial capital relative to that of labor, which we previously noted, along with the declining real interest rate (normalized to output prices) and the increases in publicly financed agricultural research, all have contributed to the steady increase in farm size by providing those farm operators who truly try to make farming a business the incentives to trade financial capital, i.e., mortgages (for purchased land) for labor.

CONCLUSIONS

Following Edward's insight that at the aggregate level the productivity of the farm sector is partly a function of structure, we used a decomposed NBRM of the U.S. farm sector to quantitatively evaluate differing characteristics of the production processes for three farm-size classes in American agriculture and the strength of several economic forces that influenced the changes in farm structure during the 1960–96 period. These characteristics of the production process, in turn, influenced structural changes in the U.S. agricultural sector. The stylized facts of structural change in the U.S. agricultural sector have been a simultaneous decline in the number of small-size farms and increasing production concentration within large-size farms. We have evaluated the effects on the number of farms in each size class of two types of structural change: single-input-related technological change and total-input-related (induced) technological change. If the input price elasticity for the number of farms in each size class is negative (positive), farms in that size class are considered to have an input-using (saving) technology for that input. We found small-size farms to have input-using technology for labor and financial capital, and input-saving technology for machinery capital; medium-size farms to have input-using technology for machinery capital and input-saving technology for labor and financial capital; and large-size farms to have input-saving technology for labor and financial capital.

If the sum of all input elasticities for the number of farms in each size class is negative, farms in that size class have economies of size, and when the sum is nonzero the production technology is nonhomothetic. We found that economies of size exist for small-size farms, while the production technology is nonhomothetic for all size classes.

If the MRTS of labor for financial capital increases (decreases) as the size of farm increases, technical progress increases (decreases) the marginal product of financial capital relative to that of labor. Estimating the MRTS of labor for financial capital from the decomposed NBRM provided insights into this relationship for the U.S. farm sector. We found that the marginal product of labor is greater than the marginal product of financial

Table 4. Effect of input prices, agricultural programs, and agricultural research spending on the number of farms by size group and on the decline in farm numbers, 1960–96

	Size group			Decline in farm numbers
	Small	Medium	Large	
Wages	neg	pos	pos	Contributed
Financial capital	neg	pos	pos	Contributed
Machinery capital	pos	neg	neg	Slowed
Agricultural programs	pos	NA	neg	Slowed
Research spending	NA	NA	NA	Contributed

na = not applicable.

capital for small-size farms, and that the marginal product of labor declines as farm size increases. The marginal product of financial capital is greater than the marginal product of labor for medium-size and large-size farms. The MRTS of labor for financial capital increases as the size of farm increases from small-size farms to medium-size or large-size farms. In the spirit of Hick's definition of the neutrality of technological change, we find the existence of biased technological change for financial capital. The marginal product of financial capital relative to that of labor increased in the U.S. farm sector. Given historic factor price ratios, this gave an incentive for farmers to substitute financial capital for labor to increase the financial capital–labor ratio.

Our single-equation decomposed NBRM succinctly and efficiently measures the strength of several economic forces that influenced the changes in U.S. farm structure during the 1960–96 period. Table 4 presents a summary of our results. The increasing normalized wage rate, the declining normalized financial capital cost, and the increasing normalized agricultural research expenditures significantly increased the concentration of agricultural production at the farm level. On the other hand, normalized government farm-program payments and the increasing normalized machinery price had the opposite effects on farm production concentration, slowing the drop in the number of small-size farms. The wage, financial capital price, and machinery capital price effects are logical competitive adjustments given the prevailing factor prices normalized by the farm output price. The effects of normalized government farm-program payments and normalized agricultural research expenditures are less straightforward.

Although government farm programs provide some benefits to many farms, the effects on farm structure are at some levels paradoxical. Paradoxical because during recent years the preponderance of agricultural program payments have gone to large farmers, yet we find that government program payments have had a positive effect on the number of small farms and a negative effect on the number of farms in the large-size farm category. This result is however, consistent with our other results. We find that economies of size exist for farms in the small-size farm group. Thus, left to the market, the economic forces exerted by economies of size would reduce the number of small-size farms as their operators compete with each other to gain access to more farm resources to get larger and take advantage of economies of size. And, the existence of these economies of size implies that farms in the small-size farm group have higher per unit costs than farms in

the medium-size and large-size groups. When farmland or other farm resources become available, operators of farms in the medium-size and large-size groups may be better able to compete for these resources, exerting further pressure on the number of farms in the small-size farm group to decrease. However, government program payments likely provide extramarket resources that some operators of small farms use to hold on to their farm resources. As a result, these farms are less likely to be “on the market,” allowing these small farms to survive for another time. Agricultural programs have effectively slowed the loss of resources available to operators of farms in the small-size farm group, slowing the loss of farms from that group. The positive effect on small-size farms is a slowing of their decline in numbers.

We also found that normalized agricultural research expenditures had a negative effect on the total number of farms. This result supports the popular belief that publicly funded agricultural research has provided the basis for highly innovative agriculture, which is geared toward capital-intensive, large-scale farms who benefit from technological progress by reducing their average production costs, but coincidentally, also reducing the total number of farms.

The number of small-size farms steadily declined from more than 3.8 million in 1960 to 1.7 million in 1996, while the number of medium-size farms increased from 95,000 to 212,000 and the number of large-size farms increased from 24,000 to 141,000. Our results describe the technological environment in which these changes occurred. We found the marginal product of financial capital larger for medium- and large-size farms than for small-size farms, which allowed medium- and large-size farms to benefit more from the capital bias of the technological innovations that occurred during this period. Furthermore, we found that the MRTS of labor for financial capital increases as the size of farm increases from small-size farms to medium-size or large-size farms, and that small-size farms experience economies of size. Finally, we found that all these forces reinforced economic incentives to increase the size of small farms which, with a relatively fixed farmland base and an inelastic and slowly growing demand for farm output, lead to a crowding out of farms in the small-size class. Only agricultural programs and rising real machinery prices countered these forces.

NOTES

¹We thank an anonymous reviewer for a concise description of the process by which the Edward's effect comes about, i.e., New technology is made available but the diffusion process is perhaps quite slow and is strongly related to structure. Hence, the first round effects of the technological changes are only from the few, large adopters. But over time, as laggards adopt or retire/exit and are consolidated into the larger firms, the impact of the technology continues to expand, even though time has elapsed since the technology was introduced. The full effects of the technical change would only be evident when/if full diffusion occurred.

²In those cases where the number of farms in any size class results in sufficient control over inputs or output such that these farms influence prices, prices are endogenous. As a referee pointed out for the case of an aggregate analysis of the changing structure of farm firms, instrumental variables should then be used to account for the effect of this simultaneity on the parameters estimated.

³ N_i is, of course, discrete, but is treated as though it were continuous.

⁴The authors are indebted to a referee for insights leading to the derivation of Eq. (9).

⁵See Kim et al (2001), for a similar application for the U.S. flour-milling industry.

⁶The authors realize that large farms employ most hired farm workers. If the farm wage rate is a proxy for the general wage rate, however, a higher farm wage rate both raises the labor cost for the small farm operators that employ workers and the opportunity cost of the time of operators of small farms. Both economic forces encourage labor shedding by small farms.

⁷Our cost function models the economic forces that pressure the farms to exit their present size class or enter a different size class. The data on the number of farms in each size class do not allow us to model the exit/entry process per se. The data on the number of farms in each size class produces snapshots of the farm structure at points in time. Annual changes are net changes like one gets from net stock changes when comparing two balance sheets. The data series does not provide the dynamics of getting from one point to the other, as needed to model the exit/entry process.

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APPENDIX

Proposition 1. If $E_i = \sum_k [\partial \ln N_i(y_i) / \partial \ln p_k] \neq 0$, the production technology is non-homothetic.

Proof. Following Antle (1984) and Kuroda (1987), the production technology is non-homothetic if $Z_i = d(\ln s_k) / d(\ln y_i) \neq 0$, where $s_k = [p_k x_k(y_i) / c_i(y_i)]$ and $d(s_k) = [p_k x_k(y_{i+1}) / (c_{i+1}(y_{i+1}) - p_k x_k(y_i) / c_i(y_i))]$ assuming continuity. Therefore,

$$\begin{aligned} d(s_k) / s_k &= [p_k x_k(y_{i+1}) / c_{i+1}(y_{i+1}) - p_k x_k(y_i) / c_i(y_i)] \\ &\quad \times [c_i(y_i) / (p_k x_k(y_i))], \text{ and using equation (6),} \\ &= \eta(y_i) [\eta(y_i) - \eta(y_{i+1})]. \end{aligned}$$

Then,

$$\begin{aligned} Z_i &= d(\ln s_k) / d(\ln y_i) \\ &= [c_i(y_i) / d(c_i)] [\eta(y_i) - \eta(y_{i+1})], \end{aligned}$$

where $\eta(y_i)$ is the elasticity of total costs associated with the production of y_i from the i th size farms. $Z_i = 0$ iff $\eta(y_i) = \eta(y_{i+1})$, which occurs if $E_i = 0$. Q.E.D.